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VALIDATION OF MULTILAYERED CLOUD PROPERTIES USING A-TRAIN SATELLITE MEASUREMENTS

Yuhong Yi[1], Patrick Minnis[2], Jianping Huang[3],

Sunny Sun-Mack[1], Yan Chen[1], Kirk Ayers[1]

[1]SSAI, Hampton, One Enterprise Parkway, Hampton, VA, 23666

[2]NASA Langley Research Center, Hampton, VA, 23666

[3]College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000

ABSTRACT

Multilayered clouds are a common, very important component in the atmosphere, affecting both the radiation budget and hydrological cycles. Accurate characterization of the vertical and horizontal distribution of clouds and their properties is essential for simulating the role of clouds in weather and climate models. Several passive remote sensing methods for retrieving multilayered cloud properties have been developed, but have been difficult to validate due to the lack of observations from active sensors. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite and CloudSat launched in 2006 provide rich information about the vertical structure of clouds. In this study, the *Aqua* Moderate-Resolution Imaging Spectroradiometer (MODIS) cloud properties derived for the Clouds and the Earth's Radiant Energy System (CERES) Project merged with CALIPSO and CloudSat profile data are used to study an example set of multilayered clouds. Assuming that the lower-layer cloud properties (such as height, temperature, optical depth and liquid water path) are obtained from CloudSat, the properties of the upper cloud layer are retrieved from the multilayer cloud retrieval system (MCRS) and then validated using of the observations from CALIPSO and CloudSat.

Index Terms**—** Multilayered, CERES MODIS, CALIPSO, CloudSat, MCRS, CO2-Slicing

1. INTRODUCTION

Clouds affect both the hydrological cycle and the energy budget of the Earth. Cloud properties (such as spatial location, temperature, horizontal and vertical distribution of liquid/ice water, optical thickness, particle size and shape) are crucial for determining radiation and heat balance [1]. Observations from space offer a powerful tool for the study of the interaction between clouds and radiation and for the retrieval of cloud properties. Moreover, satellites are clearly the only practical means for obtaining measurements over the entire globe. Furthermore, recent improvements in spatial and spectral resolutions of satellite-borne sensors have facilitated the development of more sophisticated retrieval procedures to estimate new cloud products with enhanced accuracy. However, current satellite cloud retrievals based on passive observations usually rely on the assumption that all clouds consist of a homogenous single layer, despite the frequent occurrence of cloud overlap conditions. Indeed, climatologically about 40% of the clouds are multilayered in the inter-tropical and southern Pacific zones, while about 50% are multilayered at mid-latitudes. Thus, cloud overlap often causes large errors in the retrievals of some cloud properties.

With the 2006 launch of the CALIPSO and CloudSat satellites into orbit behind the *Aqua* satellite, a constellation of satellites known as the A-Train was formed. Coincident profile information from CALIPSO's lidar and from CloudSat's radar offers a unique opportunity to map the vertical structure of clouds over the globe with accuracy never before realized. The combination of these data with observations from other A-train instruments, such as CERES and MODIS, will lead to new insight into cloud structure, aerosol climate effects, and more accurate estimates of surface longwave fluxes and atmospheric heating rate profiles that are needed to improve climate prediction.

Recently, several methods have been developed to detect multilayered clouds and to estimate the properties of those clouds classified as multi-layered. The discrepancy between cloud-top pressure derived from a CO_2-slicing retrieval and the IR-based cloud pressure has been exploited to detect overlapped clouds and retrieve the properties of each layer over a large portion of the Earth [2, 3]. Combining visible and infrared (IR) retrievals of cloud properties with microwave retrievals of cloud water temperature and liquid water path (LWP) appears to be a promising approach for detecting and retrieving overlapped clouds [4, 5, 6].

In this study, the integrated Aqua CERES MODIS cloud properties, CALIPSO and CloudSat profile data are used to a multilayered cloud system. The properties of the upper cloud layer can be retrieved from the multilayer cloud retrieval system (MCRS) [5, 6] and enhanced IR-CO_2 technique [9]. The MCRS typically uses passive microwave data to determine the properties of the low-level water clouds, but in this study, the lower water cloud properties (such as height, temperature, optical depth and liquid water path) are obtained from the CloudSat radar. Further more the upper cloud optical depth, ice water path can be validated using of the observations from CALIPSO and CloudSat.

2. DATA AND METHODS

Single-layer (SL) [7, 8] and pilot multi-layered [5, 6, 9] cloud properties derived from 1-km *Aqua* MODIS radiances using the CERES project cloud retrieval algorithms were matched and merged with CALIPSO and CloudSat products (hereafter called C3M data). The SL CERES cloud properties are determined from the radiances using updated versions of the daytime Visible Infrared Solar-Infrared Split Window Technique (VISST) and the nighttime Solar-infrared Infrared Split window Technique (SIST) [7, 8]. The products include cloud temperature, height, thermodynamic phase, optical depth, effective ice crystal diameter D_e, ice and liquid water paths and other cloud properties. The enhanced IR-CO_2 method using one IR channel at 11 µm and one CO_2-absorbing channel at 13.3 µm is used to detect multi-layered clouds and retrieve the upper and lower cloud properties [10]. The CERES-MODIS cloud properties are merged with the CALIPSO Vertical Feature Mask (VFM), and Cloud Layer and Cloud Profile data and the CloudSat Cloud Scenario Classification (CLDCLASS) and Cloud Water Content profiles. The three different data sources, MODIS, CALIPSO, and CloudSat, have very different horizontal resolutions: 1 km, 333 m and 1.1 km, respectively. Both CALIPSO VFM and CloudSat CLDCLASS are first collocated to each MODIS 1-km pixel [9]. Any CALIPSO shot or the center of the CloudSat profile that falls inside the MODIS 1-km pixel box is considered as collocated with the MODIS pixel.

One day of integrated data, 15 July 2006, was processed and the results from multi-layered clouds are presented below.

3. A CASE OF MULTI-LAYERED CLOUD

Careful examination of all of the merged C3M data yielded a 300-km orbit segment. Its pseudocolor RGB (R: 0.64 µm, G: 1.6 µm, B: 3.7-11 µm temperature difference) image (left panel of Fig. 1) shows lower water clouds overlapped by upper-level thin, transparent ice clouds (purplish, grayish and pinkish). The distribution of SL VISST-retrieved cloud phase, water or ice, is shown in the right panel of Fig. 1. The upper-level ice cloud layer extends over the entire length of the image, as confirmed by the CALIPSO VFM data (white area is cirrus cloud in Fig. 2). This upper ice cloud layer is transparent and located above 8 km. Although its geometrical thickness ranged from 1.5 to 3.5 km, its optical depth is very small, varying from 0.1 to about 2. The upper-layer ice cloud layer detected by CloudSat is shown as light green. The vertical and horizontal extent of the ice clouds detected by CloudSat is less than that detected by CALIPSO due to the radar's reduced sensitivity to thin cirrus clouds.

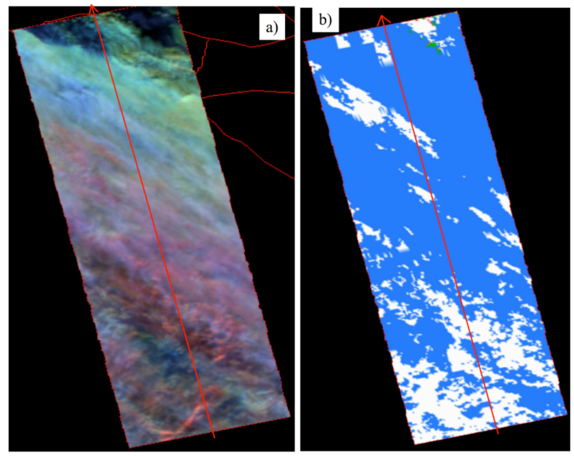

Figure 1. *Aqua* MODIS (a) pseudo-color RGB image, 072658 UTC, 15 July 2007 and (b) VISST-derived cloud phase (liquid, blue; ice, white).

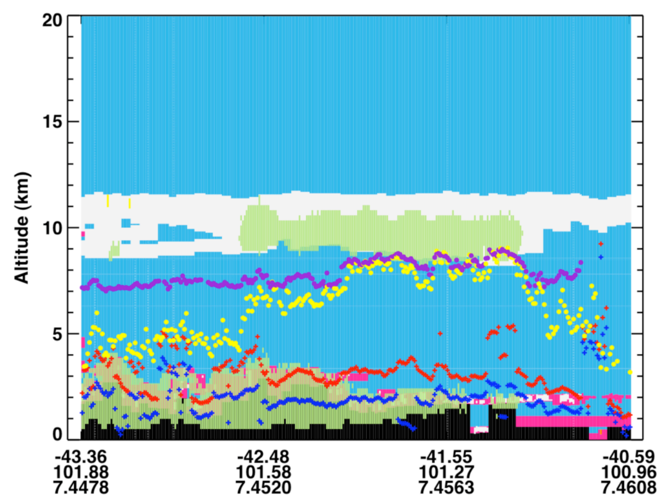

Figure 2. CALIPSO vertical feature mask for 072658 UTC, 15 July 2007 with overlaid *Aqua* CERES-MODIS cloud top height (red plus signs) and base height (blue plus signs). Light green areas are cloud layers detected by the CloudSat. Yellow dots represent cloud top height detected by original 4-channel CO_2 slicing method. Purple dots denote cloud-top height detected by enhanced IR and CO_2 channel CO_2-slicing method.

The low-level water clouds are detected both by CALIPSO (magenta area) and CloudSat (green area), although some the CALIPSO lidar returns are attenuated in the water clouds. The vertical structures of low water clouds are well defined by the CloudSat cloud layer data. The cloud top and base heights derived from the VISST SL cloud retrieval technique are marked as red and blue dots in Fig. 2. It is evident that the cloud top heights derived by the VISST are far below the upper ice cloud layer. They are between the lower and cloud top and the upper cloud base in the right half of the image, but mostly track the lower cloud top height on the left side of the image. Presumably, the small optical depths of the upper cloud had little impact on the retrieved height on the left side. The cloud top heights (yellow dots shown in Fig. 2) retrieved by using the 4-channel CO_2-slicing method are much higher than those from VISST, yet even they are still lower than the cloud-base heights detected by the CALIPSO. The cloud top heights detected by the enhanced 2-channel IR-CO_2 method are also lower those detected by the CALIPSO and by the CloudSat when it detects the higher ice clouds.

The effective particle size (in radius) profile derived from the CloudSat data are vertically averaged into cloud layer effective particle sizes (shown in Fig. 3). The effective radius of the water cloud droplets (shown in blue) varies from 8.5-13 µm. The effective radius of the ice cloud particles (shown in red) is about 30-55 µm, equivalent to 70-110 µm in effective ice diameter. For the multilayered clouds shown in Fig. 1, the VISST ice cloud particle effective radius (green in Fig.3) is smaller than that from CloudSat, but the VISST water cloud droplet radius (orange in Fig. 3) is overestimated due to the existence of upper-layer cloud. Conversely, the upper cloud cause the ice crystal size underestimate when VISST retrieves the cloud as ice.

The CloudSat-derived ice/liquid water contents are integrated into ice/liquid water path (shown in Figure 4, ice water path in red and liquid water path in blue for CloudSat) by multiplying the cloud layer thickness. It is found that the VISST SL total cloud water paths are significantly underestimated for the first 200 km track.

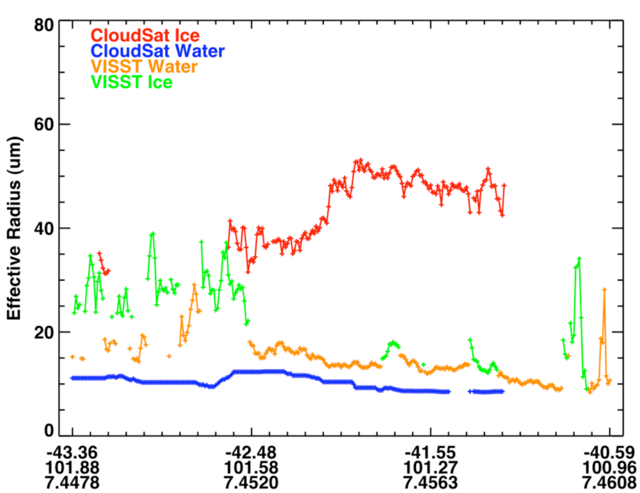

Figure 3. Effective particle sizes derived from CloudSat and VISST for 072658 UTC, 15 July 2007**.**

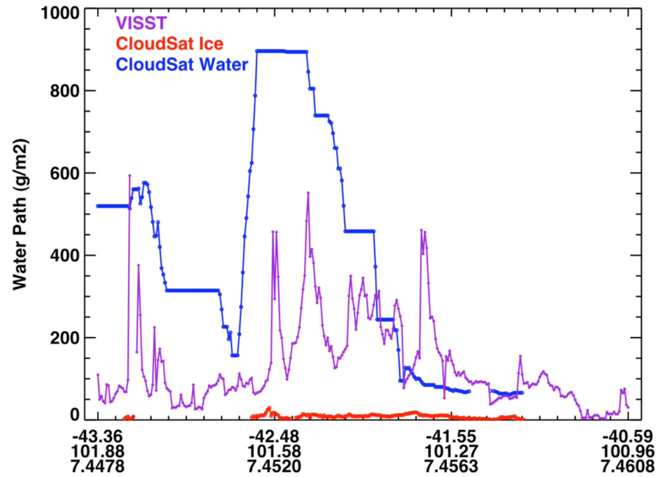

Figure 4. Water paths derived from CloudSat and VISST for for 072658 UTC, 15 July 2007**.**

Where the multilayer clouds are detected by either CALIPSO and/or CloudSat as shown in Fig. 1 and the integrated liquid water contents, geometric thickness and particle size of lower water clouds can be derived from the CloudSat data, the optical depth of the upper ice clouds can be retrieved using the MCRS.

The optical depths of upper ice clouds derived from the MCRS (in blue) and CALIPSO (in red) are shown in Fig. 5. When the upper ice clouds are optically thin (<0.5), i.e, the optical depths from CALIPSO are small, the optical depths from MCRS agree well with CALIPSO; when the upper layer clouds are relatively optically thick (>0.5), the optical depths from MCRS are mainly underestimated. The ice cloud optical depths of the upper ice cloud derived with the enhanced IR-CO_2 technique (green in Fig. 5) agree well with the CALIPSO values when the latter are ~ 1 or greater.

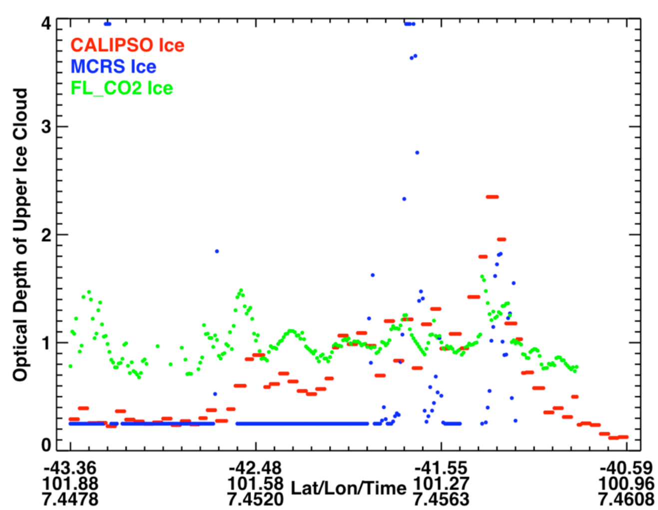

Figure 5. Optical depth of upper layer ice cloud retrieved from MCRS (blue dots) and 2 channel CO2 slicing method (green dots). Optical depths from CALIPSO are shown in red dots.

4. DISCUSSION AND FUTURE WORK

Although only one case is analyzed here, it is found that cloud overlap can produce large errors in many retrieved cloud microphysical properties, such as IWP, cloud height, optical depth, phase, and particle size, even with the newly developed multi-layered retrieval methods. The influence of liquid water clouds and precipitation on the radiances observed at the top of the atmosphere is one of the greatest impediments to accurately determining cloud ice mass for multi-layered systems with ice clouds above water clouds. The optical depth derived from the reflected visible radiance represents the combined effects of all cloud layers. When the entire reflected radiance is interpreted with an ice/water cloud model, the optical depth of the ice/water cloud can be severely overestimated/underestimated because the underlying water cloud can significantly increase the reflectance. It is clear that the underlying clouds must be properly characterized for a more accurate retrieval from overlapped cloud systems.

With the availability of CALIPSO and CloudSat data, many more multilayered cloud cases will be analyzed and validated.

5. ACKNOWLEDGMENTS

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